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Michaels, C.F.; de Vries, M.M.

published in
Journal of Experimental Psychology: Human Perception and Performance
1998

DOI (link to publisher)
10.1037/0096-1523.24.2.526

document version
Publisher's PDF, also known as Version of record

Journal of Experimental Psychology:
Human Perception and Performance
1998, Vol. 24, No. 2, 526–546

0096-1523/98/$3.00

Higher Order and Lower Order Variables in the Visual Perception of Relative Pulling Force

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In 7 experiments, undergraduates judged the force exerted by a videotaped standing puller, a computer-generated (stick-figure) puller, or a computer-generated inverted pendulum. Single and stepwise multiple regression analyses determined the kinematic variables exploited by the participants. Results show that (a) judgments correlated highly with force and improved with feedback; (b) judgments correlated more highly with lower order kinematic variables than with force itself; (c) participants differed in the kinematic variables exploited; (d) participants changed over blocks of trials in the variables exploited; (e) some participants used compound kinematic variables; (f) the variables exploited depended on the type of feedback; and (g) judgments to upright pullers, inverted pullers, and simple pendula showed the same qualitative patterns. Implications for theories of direct perception, directed perception, and heuristics are considered.

The experiments reported here grew out of an informal observation made in the context of viewing movement registrations of humans engaged in the stand-and-pull task (e.g., Lee, Michaels, & Pai, 1990). In that task, pullers stand erect, bimanually gripping a handle at elbow height, and attempt to make brief horizontal pulls to specified peak target forces without moving their feet and while holding their forearms steady and parallel to the floor. In analyzing the movement registrations in that experiment, we found that we were good at estimating the target force from looking at the kinematics of stick-figure reconstructions created by connecting the successive joint markers (i.e., ankle, knee, hip, shoulder, elbow, and wrist). The research reported in this article follows up on this informal observation. A more formal analysis of perceivers' abilities to estimate the forces a body exerts on an unyielding environmental support (or, equivalently, reactive forces that the support exerts on a body) would be a useful addition to the literature on the kinematic specification of dynamics (KSD) and the perception of dynamics. The goal of our article was to provide such an analysis.

The KSD principle holds that because kinematics (motions) follow lawfully from kinetics[1] (forces and masses), information specifying kinematics thereby provides a basis for perception of, or action with reference to, kinetics (Runeson & Frykholm, 1983). For the visual case, to which we limit ourselves here, experimental evidence suggests that individuals are indeed able to report a variety of mass- or force-related properties such as relative masses of colliding objects (Flynn, 1994; Runeson & Vedeler, 1993; Todd & Warren, 1982), bounciness of balls (Warren, Kim, & Husney, 1987), and, with point-light kinematics, the activity in which a person is involved (Johansson, 1973, 1976), the identity and the gender of the acting person (Cutting & Kozlowski, 1977; Kozlowski & Cutting, 1977), lifted weight (Bingham, 1993; Runeson & Frykholm, 1981), caught weight (Henderson, Bush, & Stoffregen, 1993), and even deceptive intention (Runeson & Frykholm, 1983).

Neither the optical specification of kinetics by kinematics nor their perception is without limit. Absolute kinetic variables are not specified optically. For example, because acceleration is net force divided by mass, for the net force to be known, mass must be known (either by virtue of perception or memory). In the research on mass estimation cited earlier, for example, observers were asked to make relative mass judgments (which mass is heavier) of unknown objects (Runeson & Vedeler, 1993; Todd & Warren, 1982); they can also make judgments about absolute weight when made relative to an (average-sized) human lifter (Bingham, 1993). However, even when the kinematics specify the kinetics, perceivers can have difficulties; these are most apparent in cases of angular motion, for example, balls rolling down inclines (Gilden & Proffitt, 1989; Proffitt & Gilden, 1989), in which mass distribution determines how motions are affected by forces and torques. Indeed, Proffitt and Gilden have observed that gyroscopes and tops, whose

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We thank Theo de Haan and Richard Casius for technical support and Raoul Bongers and Renate Albers for help with experiments and analyses. We also thank Geoffrey Bingham, James Cutting, Jean Haskell, Dennis Proffitt, Sverker Runeson, John Stins, and Bill Warren for comments on previous versions of this article and Michael Turvey for suggesting Experiment 5.

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[1] In the remainder of this article, we use the term kinetics rather than *dynamics* to avoid confusion with the various meanings of *dynamics*.

motions are based on the conservation of angular momentum, are toys precisely because their behavior is unexpected. How, when, and why these and related perceptual or cognitive difficulties occur constitute a sizable body of literature on "naive physics."

The KSD principle is explicitly about the availability of information that specifies kinetics; it is not a theory of perception (Runeson & Vedeler, 1993). Perceptual theories, in turn, differ in their claims about how such information might or might not be exploited; three theories are of interest in this article. The *direct perception view* holds that perception is specific to information, that is, the perception of kinetic property X entails the detection of a single (perhaps compound) kinematic variable Y that specifies X (Turvey & Shaw, 1978). The *directed perception view* holds that the perception of X entails any of several variables that redundantly specify X (Cutting, 1986, 1991). The *heuristics view* holds that kinetics-specifying kinematics are not used but that single, lower order variables, together with (often naive) beliefs about mechanics, permit inferences about kinetics (Gilden, 1991; Proffitt & Gilden, 1989).

As different as these theories appear to be at first blush, it is not a simple matter to distinguish among them experimentally. First, these descriptions are shorthand versions of what accomplished perceivers do. Behind the direct (and directed) perception versions are carefully articulated arguments about the meaning of the term *specification*, the nature of perceptual information, and a recognition of, if not emphasis on, a role for perceptual learning. They are theories of what perceivers do in normal (often well-learned) situations of perceiving and acting. The heuristics view, on the other hand, usually makes a negative case—that perceivers ought not be able to accurately report certain properties. Proffitt and Gilden (1989), for example, claimed that perceivers' judgments are limited by the dimensionality of the information they can detect (particle motions, but not extended body motions) and by the quality of their (tacit) knowledge of physics; therefore, heuristics that exploit single, simple, and nonspecific cues are likely to be error prone.

Attempts to evaluate the theories have investigated whether perception and actions reflect kinetics-specifying variables or variables that do not specify kinetics. The perception of ball bounciness, for example, has shown dependence on lower order variables (Warren et al., 1987). Most of the debate recently has been in the context of the colliding-balls paradigm (Gilden & Proffitt, 1989, 1994; Proffitt & Gilden, 1989; Runeson, 1995; Runeson & Vedeler, 1993; Todd & Warren, 1982). Much of the debate concerns methodology: How does one best determine the point of subjective equality? Should simulations or real events be used? Are both pre- and postcollision kinematics necessary? Do failures to detect kinetics occur precisely because researchers do not present the kinematics to which smart mechanisms are sensitive (Runeson & Vedeler, 1993)? Hecht (1996) claimed that both the theories of direct perception[2] and heuristics are, because of various escape clauses, in fact not falsifiable as general theories and therefore have "no explanatory power whatsoever" (p. 65). Nevertheless, we argue that one can attempt to determine what variable a perceiver exploits, whether that variable is the same over observers, what determines the variables that are used, and what the nature is of learning to perceive kinetics. Such was the tack of our research. We were interested in pitting higher order and lower order variables against one another to see which would better predict participants' judgments. Although answers to these questions are necessarily equivocal with respect to the aforementioned theories, we hope to show that they illuminate aspects of the debate and set the stage for rethinking the concept of specification and the nature of perceptual learning.

The ability of interest here, that of perceiving the force exerted by (on) a human figure on (by) an unyielding support, appears to require sensitivity to a higher order kinematic variable. To describe such a variable in more detail, we examine in the next section how force is created in bimanual pulling and what geometric and kinematic (hereafter "kinematic") variables contribute to the specification of force.

The Kinetics and Kinematics of Bimanual Pulling

Biomechanical and task constraints, along with a few simplifying assumptions, locate the essentials of force production in bimanual pulling in the horizontal motion of the puller's center of mass, as given in Equation 1 (derived in Appendix A, but see Michaels, Lee, & Pai, 1993, for a more detailed derivation):

$$F \approx \frac{m \cdot g \cdot (X + CP)}{H} - m \cdot \ddot{X}, \qquad (1)$$

where F is the force; m is the puller's mass; g is the acceleration attributable to gravity; X and CP are the horizontal components of the distances from the ankle to the center of mass and to the center of pressure, respectively; H is the height of the center of mass; and $\ddot{X}$ is the anterior acceleration of the center of mass.

Michaels et al. (1993) showed that the center of mass motions in this task could be modeled well as a three-parameter inverted pendulum, as shown in Figure 1. We briefly describe the model here because it provides a shorthand description of the parameters of a pull and because we used it to generate the simulated pulls in Experiments 2–7. The inverted pendulum is in an Earth-gravitational field and has a constant mass located at a fixed radius (r) from its axis of rotation. The mass is connected to a vertical support by an initially slack elastic cord of some linear stiffness (K). In a pull, the center of pressure is assumed to apply a constant torque about the axis of rotation (the ankle), which, together with a torque caused by gravity, accelerates the pendulum from the vertical. Assuming that

[2] Hecht (1996) actually contrasted the kinematic specification of dynamics with heuristics, but it is clear that he was not so much concerned with whether kinetics were specified but with whether they were directly perceived.

the system behaves like a conservative system, the kinematics of the pendulum, given an initial upright position, are uniquely determined by three parameters: (a) the constant torque created by the gravitational force acting through the distance from the ankle to the center of pressure (*CP*), (b) the amount of slack in the cord (*S*), and (c) the stiffness of the cord (*K*) according to Equation 2. This equation shows the center of mass acceleration as a function of these three critical parameters along with gravity, the puller's mass, pendulum radius, and a term, *W* (defined as $\sqrt{r^2 - X^2/r}$), that relates angular to linear terms and that with real pullers is always close to one:

$$\ddot{X} = \left(\frac{(X + CP) \cdot g}{r} - \frac{K \cdot (X - S)}{m} \cdot W\right)W. \qquad (2)$$

Looking at the trajectories of the center of mass motions with different values of the parameters (see Figure 2), we can see how the kinematics follow from the kinetics. The constant torque (*CP*) determines the acceleration of the pendulum from the upright. As the pendulum rotates, the torque caused by gravity increases, so the farther it rotates, the more it is accelerated by gravity. The point at which the pendulum starts to decelerate is determined by the slack of the cord. The more slack in the cord, the farther the pendulum will travel before it decelerates. Once the cord is stretched, its stiffness determines how fast the pendulum decelerates. Higher stiffness will result in a faster deceleration. The torque created by the stretching of the cord accelerates the pendulum so that it returns to the upright.

It is clear from Figure 2 that the lower order kinematic variables—the center of mass displacement and velocity—do not specify force. The same displacement can occur with different forces. Similarly, the peak velocity does not specify force; the two curves peaking at the upper right have the same peak velocity but different peak forces (689 vs. 523 N). It is a kinematic pattern that is unique to force. Equations relating force to kinematics could take several forms, and we show later how ecological constraints affect these equations. For now, we note simply that force is specified by a pattern of the center of mass accelerations, which could be represented, for example, as a time series of velocities or of displacements. If perceivers are sensitive to one of these equivalent kinematic complexes, then they should be able to make accurate estimates of relative force applied in the system; such would be expected with direct perception of kinetics.

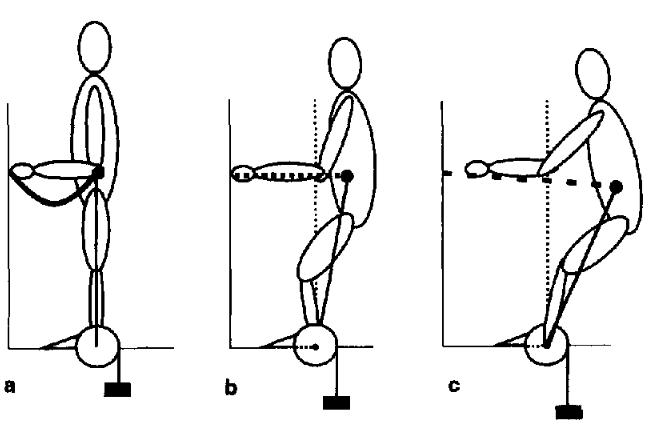

Figure 1. A schematic of the body and the inverted pendulum model. The bob moves back, playing out the slack in the cord. The cord is stretched and, according to its stiffness, exerts a force that restores the pendulum to its upright position, when another cycle begins.

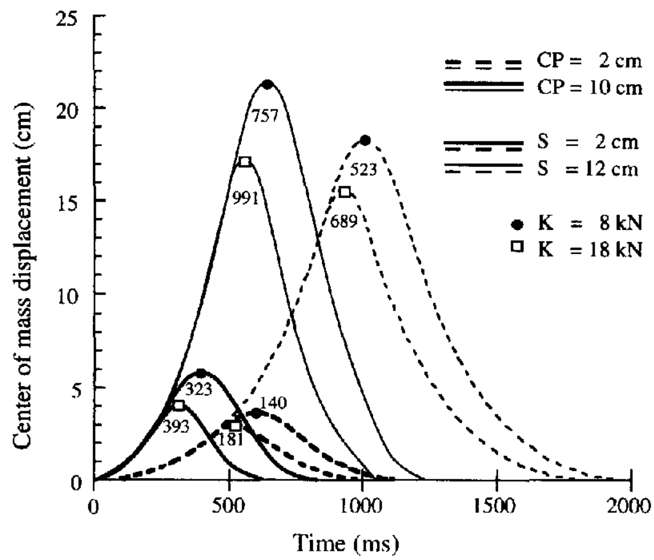

Figure 2. The center of mass trajectories for eight combinations of torque, slack, and stiffness. Variations in torque (more precisely, its moment arm, *CP*) affect how quickly the center of mass accelerates from the upright, seen in the two curve segments, dashed and solid, deviating at Time 0. Slack (*S*) determines how far the center of mass goes before it starts to decelerate, as in the differences between the bold and lighter lines. Stiffness (*K*) determines how fast the center of mass decelerates once it begins to do so, as seen in the difference between curves distinguished by circles and squares. The numbers inset at the curve peaks represent force.

In the experiments that follow, we asked perceivers to make estimates of relative pulling force over a large range of pulling forces. Single and multiple regression analyses were then used to track down the variable or variables that accounted for the systematic variance in judgments. We were particularly interested in whether observers would exploit lower order variables that do not, singly or in combination, specify force or whether they would exploit a kinematic complex that does specify force.

Experiment 1

In the first experiment we attempted to establish the phenomenon. We examined how accurately perceivers could estimate the relative pulling force exerted by a real human puller attempting to pull to various percentages of maximal pulling force and what kinematic variables perceivers appeared to exploit.

Method

Nine students from the Vrije Universiteit were paid a small fee for their participation in the experiment. They viewed a videotape depicting 250 bimanual pulls. For each pull they were asked to estimate how hard the puller pulled as a percentage of her maximal effort. If the puller appeared to pull half as hard as she could, they were to respond 50%; if it was nine tenths, they were to respond 90%, and so on.

The puller, one of us, made a series of 50 bimanual pulls on a handle attached with a chain to a force transducer. The puller was standing erect with upper arms vertical and at her side and the chain, handle, and wrist were all at elbow height. The target percentages of the 50 pulls ranged from 5% to 95%, randomly selected (with the condition that there were no gaps of more than 5%). The pulls were made in a random order. The achieved forces ranged from 66 to 1,069 N and correlated well with the intended forces ($r = .95$). The pulls were recorded on video at 40 Hz with a single camera perpendicular to the puller's sagittal plane at a distance that permitted a full view of the puller throughout the pull. Four-second–long segments of each pull were rerecorded in five blocks of 50 trials with the pulls copied in a random order in each block. A 10-s intertrial interval separated each pull.

In the experiment proper, the participants viewed the tape on a monitor controlled by computer. A pull was presented and the participant entered his or her estimate of the relative pulling force by keyboard in the 10-s interval. If the estimate was entered within 8 s, the tape continued. If the estimate had not yet been entered, the recorder was paused by the computer and restarted on a signal from the experimenter. The participant was given on-screen feedback of the correct percentage, as determined from the recordings of the force transducer, immediately on entry of the estimate.

The video was analyzed to determine the values of kinematic variables. The positions of white markers over the ankle, knee, hip, shoulder, elbow, and wrist in the video were digitized, along with several reference points, and transformed to real-word coordinates. Classical segmental analysis using mass distributions based on average female anthropometry (Chaffin & Andersson, 1984) yielded the vertical and anterior–posterior center of mass positions for each video frame. The anterior–posterior coordinates were smoothed with a low-pass cutoff frequency of 5 Hz, differentiated with respect to time to yield velocities, and a second time to yield accelerations. From these time series, the peaks of displacement, velocity, and acceleration were determined for each pull.

Results and Discussion

We begin with an assessment of the extent to which participants' estimates of peak force were consistent with the actual peak forces. Correlation coefficients were determined for each block of trials for each participant. These correlations were uniformly high ($.83 < r < .94$) and there was a significant increase[3] in the correlations over blocks of trials, $F(4, 28) = 5.15$, $p < .005$, suggesting that the feedback aided in guiding participants' attention to force information.

As emphasized in the introduction, such correlations are ambiguous; they might reflect sensitivity to a higher order variable specifying force or the use of a good heuristic—using a lower order variable or variables that correlate with force. To determine whether a simple heuristic led to such impressive correlations, we regressed judgments against two kinematic variables: the maximal displacement of the puller's center of mass (X) and the maximal velocity of the center of mass (V).[4] Correlations between judgments of force and the two kinematic variables also were uniformly high; correlations with X ranged from .81 to .93 and correlations with V ranged from .84 to .96, with the V correlation always nominally higher than the X correlation. The critical question is, then, whether the correlations between judgment and V are higher than those between judgment and force. Their Z_rs were subjected to a two-way within-subjects analysis of variance (ANOVA), with variable (force vs. V) and blocks as factors. The main effect of blocks, $F(4, 28) = 4.57$, $p < .01$, showed the expected increase in correlations over blocks. The main effect of variable, $F(3, 21) = 17.01$, $p < .005$, revealed that the average correlation for velocity was higher than that for force. The interaction did not reach significance ($F < 1$).

Stepwise multiple regression analyses of judgments against the X and V were carried out on all blocks of trials for all participants. V was always the single significant predictor. However, it also was the case that X and V were highly correlated (.95), suggesting that even with these two variables, there is a daunting multicollinearity problem. In any case, the data are consistent with the idea that all participants used a velocity heuristic.[5]

One might wonder whether there is some other variable that correlates even more highly with judgment. Is there systematic variance that is not being accounted for (albeit necessarily small because V is already accounting for 84% of the variation in individual observations)? To test this, we computed the correlations between judgments based on each stimulus and the judgments on the same stimulus on the previous block of trials. We reasoned that if there were systematic variance in judgments that we were missing,

[3] This and all subsequent tests of the significances of differences among correlations were performed on the Z transformations of the correlations rather than on the correlations themselves. $Z_r = .5[ln(1 + (r) - ln\,(1 - r)]$.

[4] Our original intention to use the center of mass acceleration as an additional predictor had to be scrapped because of multicollinearity between the variables; V accounted for 96% of the variability in the peak acceleration. This or the related problem that X and V together were multicollinear with acceleration precluded the use of acceleration as a predictor in all of the experiments reported here. Thus, there was ambiguity in our determination of the precise kinematic variables that were exploited. Note, too, that the bimanual pull arguably has only one degree of freedom (given biomechanical and task constraints, the momentary center of mass position is unique to one configuration of joint angles and positions); as such, the single degree of freedom can be expressed in a number of ways (e.g., hip position or knee angle).

[5] It also is possible that the puller used a "velocity heuristic" to produce the action. One can think of the pull as building up kinetic energy, transferring that into potential energy of the elastic element (muscles and tendons), and returning that potential to kinetic energy to bring the body to the upright position. If the stiffness (K) of the elastic element is constant over pulls, then the inertial component of the peak force will be proportional to the peak velocity. In other words, posterior velocity (presumably specified in the puller's optic flow) specifies upcoming force (see Michaels & Lee, 1996, for details).

correlations between judgments on successive trials would be higher than (or as high as) the correlations between judgments and the best kinematic predictors. If the systematic variance is accounted for by the predictors, the intertrial correlations should be lower. The reasoning was as follows: If a predictor correlates .8 with judgments on successive trials, it accounts for 64% of the variance in each, so trial n should predict only 64% of the (systematic) 64% of trial $n + 1$, which should lead to a correlation of .64. The observed intertrial correlations turned out to be considerably lower than other predictors, suggesting that systematic variation was already accounted for.

All of the individual results are presented in Figure 3, which gives the various R^2 for the five aforementioned predictor variables. We describe this figure in detail because we report the results of other experiments in similar figures.

The squares show the R^2s for the predictions based on the previous block. As noted, these tended to be the lowest of the lot, although they showed the most gain, revealing that judgments became more consistent. The diamonds show the R^2s for force; as noted, these correlations were high, but never the highest. The two kinematic predictors, X and V, are shown as open circles and plus signs, respectively. These appeared to differ somewhat among participants (e.g., X seemed a poorer predictor for Participant 8). V was an excellent predictor for all participants. Finally, the $\oplus$ shows the R^2s for the multiple regression of judgment against X and V. If there is only one significant predictor in a given graph, then the multiple R^2 equals (and overlaps) that predictor; if the multiple R^2 is higher than the other predictors, then both V and X were significant predictors in the multiple regression. To be a significant predictor, a variable must add significant predictive power beyond that of the first predictor. Later in this article we show more interesting versions of such graphs in which there were bigger differences among variables and participants, and more changes among predictors over blocks of trials.

Overall, it is clear that the judgments of force from viewing a video of a real puller were more reflective of lower order kinematic variables than of (a kinematic variable specifying) force. A combination of variables could have led to better performance; a regression of force against the kinematic predictors (including acceleration) revealed that a compound of acceleration and velocity was the best predictor. However, participants did not or were not able to discover that compound variable. This could be attributable to any number of factors, such as insensitivity to acceleration (cf. Calderone & Kaiser, 1989). Additionally, given the high intercorrelations and the consequent high level of performance that could be achieved using a single variable, the information space was not sufficiently broad to permit exploration. (The various intercorrelations among variables are presented for all Experiments in Appendix B.) That is, trying a different variable or combination of variables would not yield a sufficiently differentiated feedback to encourage change. It is interesting to speculate, in that regard, that dips in performance on later blocks, although it might indicate that the task was getting tedious, might also be attributable to participants' attempts to scope out the kinematic landscape to find a variable that led to better performance.

Unfortunately, the task demand on the puller—to generate accurate pulling forces—may have worked against creating a rich landscape of kinematic variables. Namely, the smaller the number of variables that the puller must control, the more likely the achievement of accurate pulling force. On these grounds, we decided to use computer simulations of pulls in which a richer array of kinematic variables could be created. We used this strategy in Experiments 2–6.

Experiment 2

In Experiment 2, we used computer-generated stick figures engaging in the stand-and-pull task. Our goal was to decorrelate the kinematic variables to increase the chances that participants would explore the information space and perhaps discover a variable that specifies force. Obviously, when participants viewed a real human puller, the use of a velocity heuristic was either sufficient to generate gratifying feedback, or, if it was not gratifying, there was little guidance about what other variables or compounds would improve performance. First, however, we decided to present the stick figures without feedback to obtain a performance baseline for comparison with subsequent experiments.

Although we sought to decorrelate the kinematic variables, we explicitly did not want to use arbitrary collections of those variables, as has sometimes been done in gait perception research (e.g., Todd, 1983). We agree with Runeson (1994) and Bingham, Schmidt, and Rosenblum (1995) that kinematic displays of (bio)dynamic events ought to be tightly constrained by a (bio)dynamic model. To this end, our simulations of the bimanual pull exploited the empirically supported inverted pendulum model of the task (Michaels et al., 1993), described briefly in the introduction.

Method

Twenty-seven stick-figure displays of a human engaging in the stand-and-pull task (see Figure 4) were generated. The center of mass motions were generated from the model presented in Equation 2. The factorial combination of three levels of the three parameters (i.e., torque, slack, and stiffness) yielded 27 stimulus displays. All variables were within the ranges observed by Michaels and Lee (1996) for human pullers. The levels of torque were 2, 6, or 10 cm (multiplied by an assumed mass of 70 kg and a gravitational acceleration of 9.8 m/s^2); the levels of slack were 2, 8, and 12 cm; and the stiffnesses were 8, 12, and 18 kN/m. The equation for the acceleration of the pendulum system (see Equation 2) was numerically iterated at intervals of 1 ms and the position of the bob read out every 17 ms (the frame rate of the Silicon Graphics display). (The center of mass motions in Figure 2 are those generated for this experiment; the middle value of each parameter was omitted in that figure.) In addition to the center of mass positions, the program also computed peak force and the peak

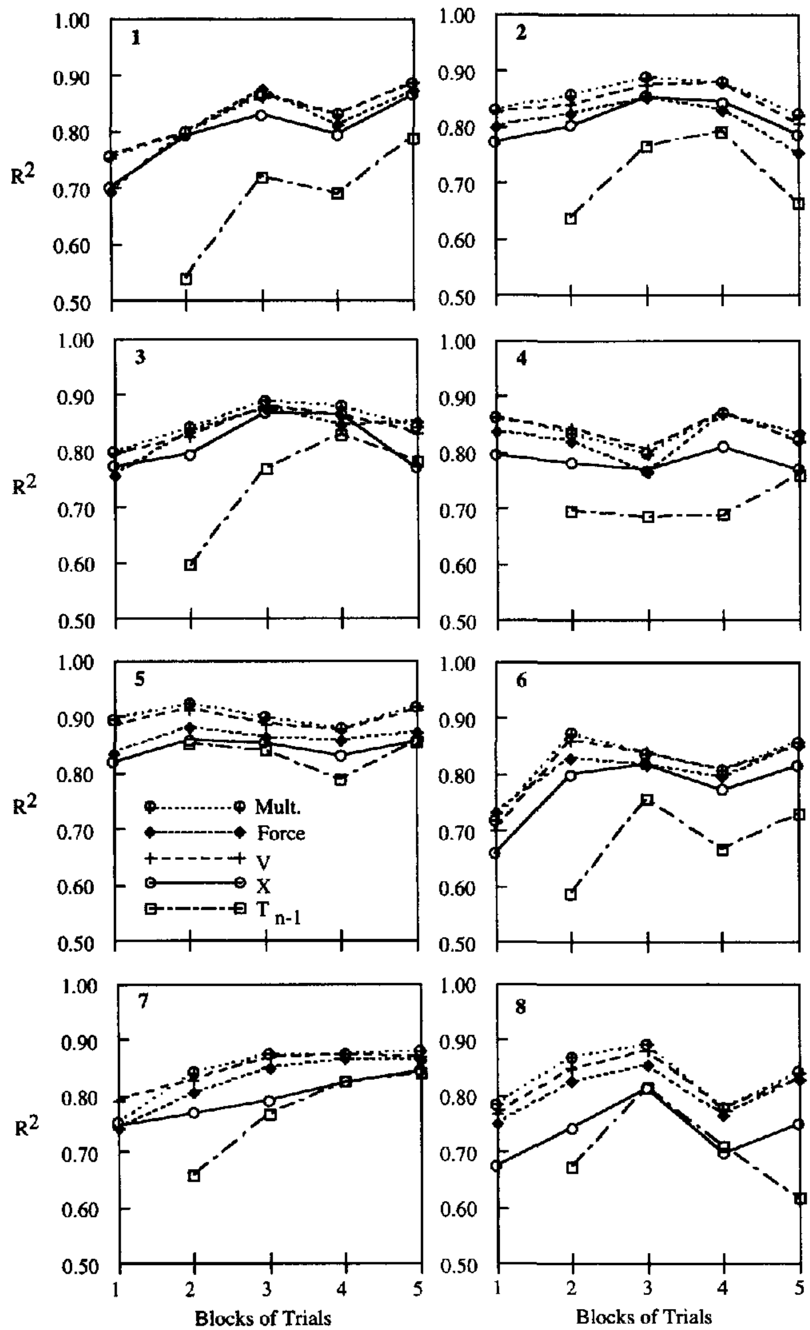

Figure 3. R^2s of the zero-order correlations of force judgments with actual force (diamonds), X (open circles), V (plus signs), and judgment on the previous trial (squares) and of the multiple correlations of force judgments regressed against both X and V ($\oplus$) in Experiment 1, which used a video display and feedback on actual force. If, on any block the o or + symbols for X and V, respectively, are not visible, they are obscured by the multiple correlation (Mult.) symbol, $\oplus$. T = trial; n − 1 indicates the previous block of trials.

displacements, velocities, and accelerations of the center of mass that, although not depicted on the screen, were specified (under the boundary conditions cited in Footnote 6) by the segment positions. The positions of the knee, hip, and shoulder joints also were computed for each center of mass position.[6] The height of the stick figure on the screen was 15.5 cm.

[6] The one-to-one relation between the center of mass position and joint positions assumes that the elbow and ankle do not move and that the spine and head complex is rigid. The joint locations were based on average human anthropometry (Chaffin & Andersson, 1984).

Each trial consisted of three consecutive identical pulling cycles. As in Experiment 1, participants were asked to estimate what percentage a given pull was of the maximal pulling force that the figure could exert. They were told that a maximal pull might or might not occur among the displays that they were to rate. The simulated range of forces, as indicated in Figure 2, was 991 to 140 N, a range of 7–1. Participants entered their estimates using a computer keyboard. Eight students at the Vrije Universiteit were given four trials each on the 27 stimuli in randomized blocks. No feedback was given.

Results and Discussion

The battery of analyses described for Experiment 1 was carried out on the data. The results are given in Figure 5. The first remarkable outcome was that 3 of 8 participants (1, 2, and 6) had no statistically significant predictors, including their judgments on previous trials. Assuming that these results were not the result of some untraceable computer glitch, we must conclude that they simply did not understand what was asked of them. We found this odd because none of the participants gave any indication that the task was impossible, unnatural, or even difficult. Indeed, one of these participants went so far as to ask whether he should take into account that the little man had made so many pulls that he must be getting tired.

Among the 5 participants whose estimates were systematic, we again found reliable correlations of judgments and force, averaging .72 (note that the figure presents R^2 rather than r). However, it was again clear that V and X tended to be better predictors than either (a kinematic variable specifying) force or judgment on the previous trial.

The multiple regression analyses showed that 3 participants (4, 5, and 8) had only X as a significant predictor (the crossed circle depicting the multiple correlation overlaps the open circle) and 1 participant (3) had only V as a significant predictor. Participant 7 had both X and V as significant predictors, at least on Blocks 2 and 3. As might be expected with no feedback, a one-way within-subjects ANOVA showed no significant improvement in correlations with judgment and force over blocks of trials.

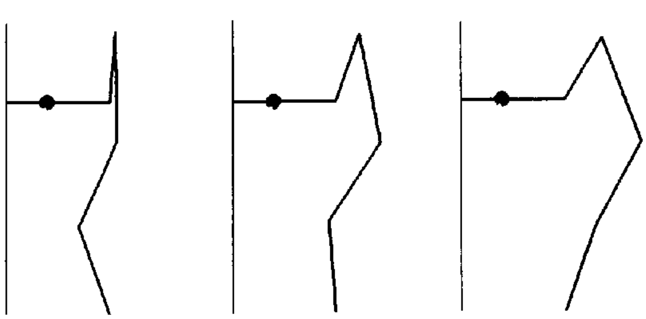

Figure 4. The stick-figure puller simulated in Experiments 2–5. The three positions are the initial position, the final position for a pull of intermediate center of mass displacement (which would also be an intermediate position for a pull with greater center of mass displacement), and the final position for the pull with maximal center of mass displacement.

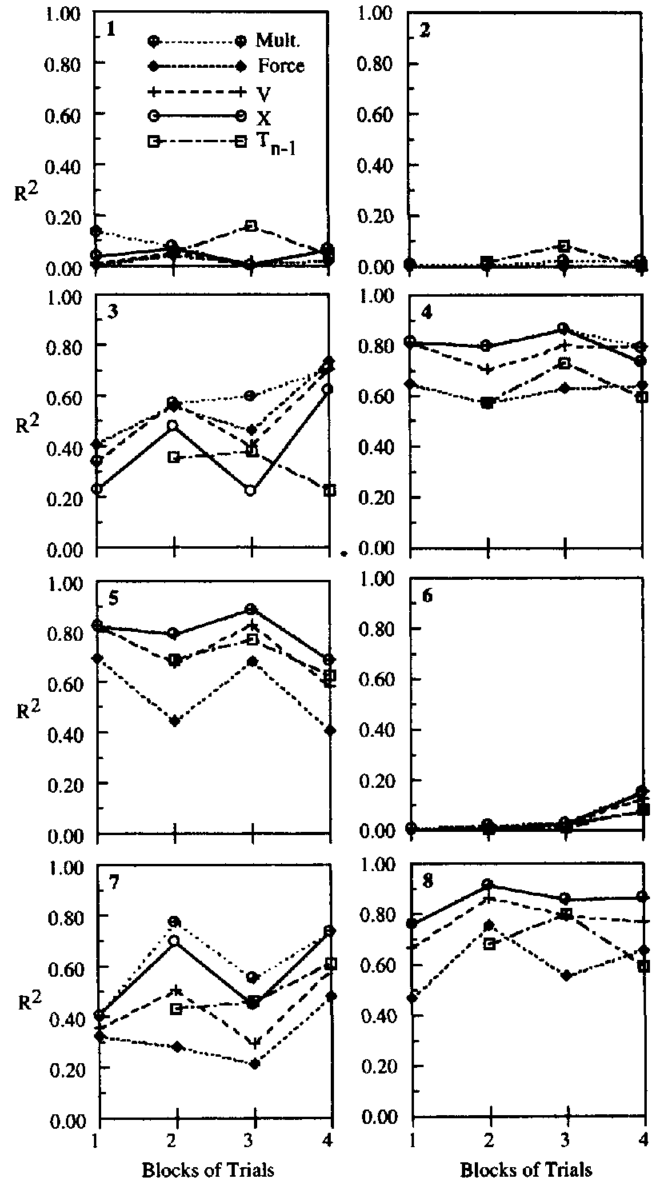

Figure 5. R^2s of the correlations for the various predictor variables in Experiment 2, in which judgments were given to a stick figure but in which no feedback was given. Mult. = multiple correlation, V = plus signs, X = open circles, T = trial, and n − 1 indicates the previous block of trials.

As in Experiment 1, the nominal variable that participants were supposed to estimate—force—correlated less highly with judgments than lower order variables, which were (merely) correlated with force, and different participants appeared to rely on different variables. Both of these observations are in clear violation of what one would expect from direct perception of force (via a kinematic variable specifying it). Instead, an explanation in terms of heuristics seems in order. In addition, arguably, three heuristics were observed, one based on velocity, one based on displacement, and one based on both.

Experiment 3

In Experiment 3, we assessed the effects of feedback. Holding out for the possibility of the direct perception of force, we examined whether participants could learn to detect a kinematic variable specifying force given the more articulated feedback than was available in Experiment 1. From a heuristics perspective, we examined whether such feedback would permit participants to learn a more effective heuristic. Note that possible heuristics are not equally effective. Analyzing the collection of stimuli from Experiment 2 (which also was used in this experiment), an X-based heuristic can yield a correlation of judgment and force of only .85 (the correlation of X and force), whereas a V-based heuristic could yield a correlation with force of .95 (the correlation of V and force). These values assume that the predictor is perceived and judged errorlessly. A combined strategy could correlate as high as .97 (the multiple correlation of force predicted by X and V).

Method

Every trial consisted of two stimuli, a standard stimulus and a test stimulus. The standard stimulus, which was the same in every trial, showed a stick figure whose motions reflected a torque of 6, stiffness of 12, and slack of 7 (the intermediate values of all parameters) and was assigned the arbitrary value of 10 force units. Participants were instructed to scale the force applied in the second stimulus with respect to the standard. If twice as much force was applied the participant's response should be 20, and if half as much force was applied the response should be 5, and so on. Both the standard and the test display consisted of three identical pulling cycles. After the participant had entered his or her score on the keyboard, the correct answer was displayed on the monitor and then followed by the next trial. The experiment consisted of six blocks in which the 27 stick-figure displays were presented in a random order. The nine naive participants were paid a small fee.

Results and Discussion

Figure 6 shows the correlation plots for 8 of the 9 participants in Experiment 3. Casual comparison with the results of Experiment 2 shows that performance was considerably better. All the participants had high correlations with force, and it is obvious that one or another of the predictors could account for most of the variance in judgments. Moreover, except for Block 3 for Participant 2, predictions based on the previous trial were lower than for other predictors, indicating that the predictors captured all the systematicity in variance.

Although it was clear that some participants showed improvement—and a one-way within-subjects ANOVA showed that over subjects, the trend toward improvement in force judgments over blocks was significant, $F(5, 40) = 5.82$, $p < .001$—it is also noteworthy that the judgment–force correlations were already high on the first block of trials. As high as the correlations with force were, however, we again observed that they were never the highest; as in the previous two experiments, it therefore appears that participants' judgments were not based on a kinematic variable specifying force.

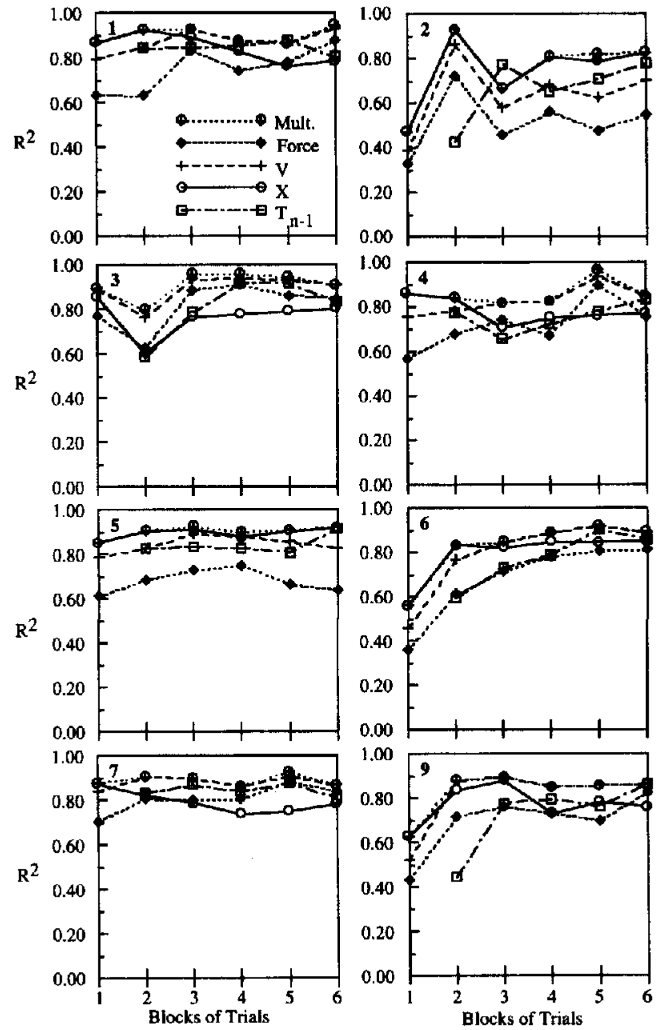

Figure 6. R^2s of the correlations of force judgments with the various predictor variables in Experiment 3, in which judgments were given to a stick figure and in which feedback on actual force was given. Mult. = multiple correlation, V = plus signs, X = open circles, T = trial, and n − 1 indicates the previous block of trials.

As to which kinematic variables best predicted judgments, we found differences both among and within participants. Participants 2 and 5 showed a continued reliance on X; their V correlations were below the X correlations and the multiple correlations sat reliably on the X correlations. Participants 8 (not depicted in Figure 6) and 9 persevered with V. The other participants all showed a shift over blocks in the best predictors of their judgments. Participants 1, 4, and 6 appeared to shift from X to V; Participant 3 shifted from V alone to a VX strategy, wherein both variables independently were significant factors in a multiple regression.

One might justifiably wonder whether the differences trumpeted in the previous paragraph were real or simply spurious shifts in the tangle of highly intercorrelated predictors. First, when a multiple correlation is higher than the individual predictor, it is necessarily significantly higher than the zero-order correlation. Second, differences between zero-order correlations are subject to statistical testing (see Cohen & Cohen, 1983, pp. 56–57).[7] Of the 54 pairs (9 Participants × 6 Blocks) of X and V correlations, 25 were significantly different at the .05 level and another six at the .10 level. Participant 2, for example, for whom an X strategy was claimed, showed a significant superiority of X over V on four of the six blocks. Participant 9, for whom a V strategy was claimed, also showed a significant V over X superiority on four of the six. Participant 6, for whom a shift of strategy was claimed, showed a significant X over V superiority on Block 2, a significant V over X superiority on Block 5, and both predictors were significant in the multiple regression on Block 6. Thus, although not all differences that one might note in Figure 6 are statistically significant, it is clear that differences in strategy both between and within participants are statistically reliable.

To summarize, our search for the direct perception of force again came up empty-handed. To be sure, correlations with force were high, but they were uniformly lower than to kinematic predictors that were not specific to force. In that sense, we concluded that participants appeared to use heuristics; their judgments correlated most highly with kinematic variables that, although correlated highly with force, were not specific to it. Moreover, the heuristics were not the same in all cases. Participants differed from one another in the heuristics they exploited, and some participants appeared to change heuristics over blocks of trials.

Experiment 4

The display characteristics in the first three experiments permitted a high level of performance even if participants responded on the basis of single, lower order variables. This was because there were high correlations both between peak force and peak displacement and between peak force and peak velocity. In the first experiment, basing force judgments on X alone could yield a correlation of estimated and actual force of .95; using V alone could yield a correlation of .97. In Experiments 2 and 3 those correlations dropped, but only marginally, to .85 and .95. (Participant 4's estimates in Experiment 3 illustrate the nominal success that can be achieved using displacement and velocity heuristics: Judgments correlated .93 with X on the first block and .97 with V on the fifth block; the corresponding correlations with force were .76 and .95, respectively.) If one used a compound of displacement and velocity, correlations of judgment and F could be as high as .97. The high correlations between kinematic variables and force are not necessary relationships; with appropriate manipulation of torque, slack, and stiffness, one could contrive collections of displays in which peak velocity or peak displacement would be negatively correlated with force. This may seem odd in that the variables are related to each other by physical laws; it may even seem odd to speak of correlations in the first place. The correlations refer only to the relationship among variables within a particular collection of displays. By analogy, in a set of ball throws, one could nullify the expected relationship between initial velocity and distance traveled by contriving the projection angle to increase with velocity, even to the point of establishing a negative correlation between velocity and distance.

If one wanted to further hold out for the possibility of the direct perception of force, one might argue that the participants did not come into the laboratory with their attention educated to a kinematic variable specifying force, that by virtue of the relations cited in the previous paragraph they were able to achieve good enough performance using simple variables. The question, of course, is whether a display set contrived to minimize these correlations would influence the variables that are used and perhaps even foster responsiveness to kinetics-specifying kinematics.

Experiment 4 made a step in this direction by contriving a collection of displays that eliminated the correlation between X and force and substantially reduced the correlation between V and force (to .74). If a participant uses only X in judging force in this set of displays, then judgments will not correlate with force, a fact presumably revealed through the feedback. A similar situation holds for V; reliance on V alone, although it would lead to moderate success in the task, might yield sufficiently unsatisfying feedback to motivate an exploration of the information landscape in which participants might find a kinematic variable that supports more accurate performance.

Finally, and perhaps most important, removing the correlation between X and force sets the stage for distinguishing between the use of individual variables in combination and the use of a compound variable. To appreciate the distinction between combinations and compounds of variables, imagine that two variables are both correlated with the to-be-estimated property and are not correlated with each other. A participant might detect the two variables independently, and each variable might account for a certain percentage of the variance in judgment, either on different trials or as a weighted sum on an individual trial; this would be a combination. Consider a second case, such as the situation we are setting up in Experiment 4, in which one of the variables (V) is correlated .74 with the to-be-perceived property, force, and the other (X) is not correlated with force. If a participant bases force judgments on V, the maximal correlation that could be achieved between judgments and force would be .74 (the correlation between V and force). If said participant simply added X as a separate variable, no benefit would be gained because the correlation of X and force is contrived to be zero. Imagine further that the relations among X, V, and force are as shown in the upper four curves of Figure 2 (viz. that given a particular V, the larger the X the lower the force). If this compound of V and X were used, estimates could correlate as high as .99 with force, which is the multiple correlation of force regressed against both X and V. When V is partialed out, X becomes informative; the compound of XV is greater than the sum of

[7] Cohen and Cohen's (1983) book is highly recommended as an informative, accessible, and even entertaining treatment of the uses of multiple correlation and regression in the investigation of causal relations.

its parts. Thus, if participants show a combined dependence on V and X and have high correlations with actual force, a compound variable is implicated; X is valuable only in the context of V.

The size of the judgment-force correlation is informative about what variable is not being used. An X heuristic can yield a maximum R^2 that is not statistically above zero; a V heuristic and a combination (V-plus-X) heuristic can yield a maximum R^2 that is not statistically above .552; and an X-given-V heuristic can yield a maximum R^2 that is not statistically above .979. Thus, to the extent that any observed judgment–force R^2 is above any of these values, that heuristic is eliminated as a possibility on that block of trials. Notice that this logic is subtly different from that in our earlier experiments, in which we reasoned that certain high correlations evidenced the use of particular strategies; here, the observation of certain correlations precluded the use of certain strategies.

Method

The basic technique was that used in Experiment 3. The center of mass motions of the stick-figure display were based on the three parameters: torque, slack, and stiffness. In this experiment, however, the slack parameter had only one level: 7 cm. Stiffness and torque had five levels each (6, 9, 12, 15, 18 kN/m and moment arms of 2, 4, 6, 8, 10 cm, respectively). In the resulting 25 displays, X and force had a correlation of $-.05$ and V and force had a correlation of .74.

A display with a stiffness of 12 kN/m and a torque arm of 6 cm was used on all trials as the standard against which the other displays were to be scaled. The 25 displays were presented six times in completely randomized blocks. After each trial the participant's estimate and the correct force (scaled in reference to the standard of 10) were displayed on the monitor. There were nine naive participants.

Results and Discussion

The individual correlations of estimated force with X, V, force, and the previous trial, along with the multiple correlation against X and V, are plotted according to participants and blocks in Figure 7. Inspection of the figure shows considerable differences among participants and considerable changes over blocks of trials within participants. Note that the predictions based on the previous trial were never the highest, suggesting that the analysis did not neglect systematicity.

For 6 participants (1, 4, 6, 7, 8, and 9), the correlations between judgment and force (indicated by the diamonds) were high;[8] 2 participants (3 and 5) showed moderate correlations, and 1 participant (2) showed no significant correlation. For those who did show a correlation, there was considerable improvement, although Participant 6 began with such a high correlation that there was little room for improvement. Because the three (post hoc) groups of participants (showing high, moderate, and no judgment–force correlation) maintained a fairly coherent identity across the various analyses, we do not describe the participants separately. First and most important, the sizes of the correlations with force in each group necessarily precluded the use of certain heuristics. We concluded that Participants 1, 4, 6, 7, 8, and 9 did not use an X, V, or X-plus-V heuristic because the R^2s exceeded the .552 cutoff. Similarly, Participants 3 and 5 did not use the X heuristic because their R^2s exceeded the zero cutoff.

So we know what each set of participants did not use in the way of a heuristic, but there are other imaginable heuristics (e.g., based on acceleration), and there is the possibility that the judgments were based on a kinematic variable specifying force. Do we have reason to believe that a force-specific variable was exploited, at least by some participants? Our test of this in the previous experiments emphasized the superiority of the lower level kinematic predictors (X, V, and multiple XV) over actual force as a predictor. In this experiment, we found correlations with force that were close to being the best predictors for both Participants 4 and 7. In fact, the distinction between whether these participants used a kinematic compound specifying force or whether they used a heuristic of a kinematic compound that "merely" correlated .989 with force (the multiple correlation of force regressed against velocity and displacement) seems to pale in importance. With such results, proponents of the heuristics view and the direct perception view can only bicker about the distinction between specification and correlation; we return to this slippery distinction later in the General Discussion section. For now, we discuss the remainder of the results of this experiment in heuristics terms.

Participants 1, 4, 6, 7, 8, and 9, whose judgment–force correlations excluded the X heuristic and the V heuristic, showed both X and V as significant predictors in the multiple regression analysis (on an average of five blocks per participant). What is interesting about the XV compound was that the partial correlation of X with force after velocity had been partialed out was negative. That is, for a given peak velocity, the further back the center of mass went, the lower the force (see Figure 2). Obviously, this relation held for Participants 1, 4, 6, 7, 8, and 9 in this experiment.[9]

[8] The correlations in this experiment and the two that follow were not directly comparable with those of earlier experiments because they used a more restricted range of variables (e.g., a ratio of maximum to minimum force of 2.3:1) than earlier experiments (e.g., 7:1 in Experiments 2 and 3). To illustrate the possible effect of this range restriction, the correlation of judgment and force including all participants on the last blocks of trials in Experiment 3 was .89, whereas the correlation for that data set over the more restricted range of values used in Experiment 4 was only .74.

[9] It is interesting to ask, in retrospect, whether the participants in Experiment 3 also picked up on this relationship. Remember that in Experiment 3 the zero-order correlation of X and force was .85. Of the 4 participants who had Y-then-X as significant predictors, 3 showed negative partial correlations with X. The 4th participant had a positive partial correlation; he used the "incorrect" strategy of reporting larger forces for larger displacements, given a particular velocity, with a consequently lower success on force correlations (Participant 5 in Figure 5). Relatedly, it is clear that one ought not to speak about *the VX* strategy because there are different ways that variables can contribute to judgment.

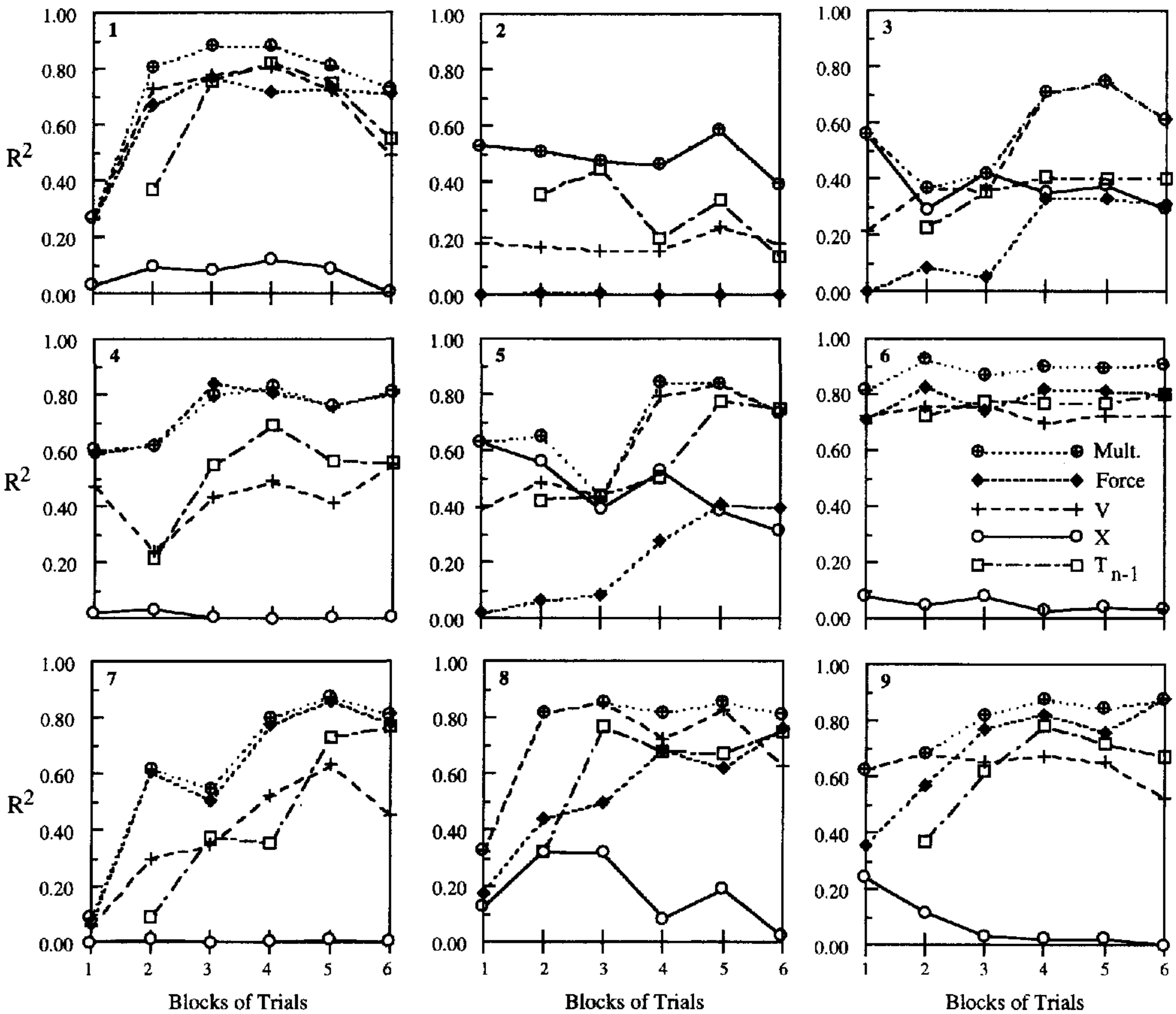

Figure 7. R^2s of the correlations of force judgments with the various predictor variables in Experiment 4, in which judgments were given to a stick figure whose kinematic variables were artificially decorrelated and in which feedback on actual force was given. Mult. = multiple correlation, V = plus signs, X = open circles, T = trial, and n − 1 indicates the previous block of trials.

Participants 3 and 5, with moderate correlations of judgment and force, began on Block 1 with *X* as the single predictor; on later blocks, their single predictor was *V*. Their initial reliance on *X*—useless with this collection of displays—gave way to reliance on the more useful but still limited *V*. This explanation is consistent with the increasing correlations of judgment and force over blocks. It is interesting that the 2 participants showed fairly high but decreasing zero-order correlations of *X* with judgment. It may be that these participants were using both *V* and *X* heuristics on different trials.

Participant 2 rounded out the range of strategies: He persevered with his reliance on *X*, reliably giving higher force estimates the larger the travel of the center of mass. He did so even in the face of feedback that, of necessity, showed no relation between his estimates and the "right" answers. To the extent that *V* had a nonzero correlation with judgment, it was by virtue of its .62 correlation with *X*.

In summary, Experiment 4 replicated several findings from the previous experiments: (a) individual differences among participants in the exploited kinematic variables; (b) changes within participants in the variables that were exploited; and (c) at least for some participants, a superiority of lower order kinematic predictors over a force-specifying variable. It also made two intriguing additions to that list. First, participants appeared to be able to use compounds in which a variable uncorrelated with the nominal variable could nevertheless contribute to accuracy. Second, the correlations of such "merely correlated" compounds could get so high that one should wonder about the utility of the distinction between specification and correlation, and consequently about the distinctions between theories of direct(ed) perception vs. heuristics, at least in this context.

In the next three experiments, we tested some general characteristics of the visual perception of force in the stand-and-pull task. Our goal in these final experiments was to determine the generality of the findings. In particular, we assessed the effects of different kinds of feedback and attempted to determine whether the observed results depend on the use of a human form or whether the same kinds of results would be found when participants were asked to make force estimates about an analogous physical system.

Experiment 5

The participants in our experiments, as a rule, did not appear to have come into our experiments as expert force perceivers. Three participants in the no-feedback Experiment 2 could have performed as well not looking at the displays. Others showed great improvement over the course of the experiment; they adapted their strategy or educated their attention to kinematic variables that correlated more highly with force. This learning suggests that feedback about some other variable might be equally effective in changing the variables that participants exploit in this task. In particular, in Experiment 5 we determined what would happen to participants' correlations when feedback was based on X or V rather than on force.

Method

Two groups of 8 participants served as observers. Both groups participated in an experiment that was similar to Experiment 4 with two notable exceptions. In the first case, there was no mention of force; instructions indicated that participants would view a stick figure that moved in a certain pattern and that each pattern had a certain value on the basis of a movement property or a collection of movement properties. Their task was to indicate what that value was on the basis of the feedback they received. The first, standard stimulus had a value of 10, and participants were to scale the value of the second stimulus with respect to the first.

Unlike in Experiment 4, participants were not given feedback about force. One group was given feedback on the maximal displacement of the center of mass of the stick figure, X, and the second group was given feedback on the peak posterior velocity of the center of mass, V. That is, the feedback given was the X (or V) of the test stimulus divided by the X (or V) of the standard stimulus. The stimuli, numbers of trials, and other details of the method corresponded to Experiment 4.

Results and Discussion

The general pattern of correlations between judgment and the various predictor variables for individual participants and blocks for the X feedback and for the V feedback were similar to those observed in Experiment 4. However, instead of emphasizing the results of individual participants, our primary concern is with the differences in performance that accompany the different feedback conditions. To this end, we performed a three-way ANOVA on the Z_rs of the zero-order correlations between judgment and the feedback variables from this experiment and those of Experiment 4. The between-subjects variable was feedback type (X, V, and force), and the within-subjects variables were blocks of trials and predictor (X, V, and force).

There were significant main effects of both blocks and variable but not feedback type. However, all interactions involving feedback type were significant. The essence of these results can be seen in Figure 8, which shows the second-order interaction of feedback type, variable, and blocks, $F(20, 220) = 8.80$, $p < .001$. The biggest effects emerged in the force and X correlations. The judgment–force correlations tended to rise for force feedback, remained steady for the V feedback, and dropped for X feedback, whereas the judgment–X correlations tended to rise for X feedback, remained steady for the V feedback, and dropped for the force feedback. Over blocks of trials, the correlations between judgment and the fed-back variable tended to increase.

We also were interested in the extent to which single versus multiple predictors were found to be significant in the multiple regression analyses. To analyze this, we counted the number of times that just X, just V, and V-then-X showed up as significant predictors in the individual participant by block cells. The results are presented as percentages in Table 1. A chi-square analysis[10] on the frequencies was significant, $\chi^2(4, N = 138) = 37.33$, $p < .001$. The results show that X feedback tended to foster reliance on X, V feedback fostered (or maintained) reliance on V, and force feedback fostered usage of V-then-X. The percentages given in Table 1 are over all blocks of trials; when the first blocks were removed, the effect was even more striking.

The results of Experiment 5 were straightforward: The variable that was fed back had a strong influence on the variables, singly or collectively, that participants came to exploit in making their judgments. This, together with the results of Experiment 2, in which no feedback was given and in which 3 participants revealed no systematicity and others wandered along with little change in strategy and no substantial improvement, revealed that the kinematic variable that came to be exploited depended critically on the implicit task demand created by the feedback. Most participants appeared to be flexible in the way they made judgments about event characteristics.

Experiment 6

The primary reliance in the first four experiments on lower order kinematic variables suggests that there may be nothing special about the displays used—that the fact that they represent a human figure engaged in a motor skill is incidental. If participants can (learn to) rely on lower order display characteristics of velocity and displacement, then one might expect that any display of a point moving in arbitrary ways might yield the sorts of results that were

[10] Cells in which no predictor was significant or in which X-then-Y was significant were few and were omitted from the analysis because they compromised minimal expected values necessary for the chi-square analysis.

observed. In Experiments 6 and 7 we examined this question by testing whether the same patterns of results would be observed with the display inverted and with a simple pendulum rather than a stick-figure human, respectively. The testing of force perception with an inverted figure was motivated by observations that inverted point-light displays often do not evoke the immediate and compelling experience of biological motion that usually accompanies upright displays (Pavlova, 1989; Sumi, 1984).

Table 1
Percentages of Blocks Showing X, V, or V-Then-X as the Significant Predictor in Multiple Regression Analyses of the Effects of Feedback in Experiments 4 and 5

	Feedback type		
Predictor	*X*	*V*	Force
X only	56	34	17
V only	28	55	27
V-then-*X*	15	11	56

Method

Experiment 4 was repeated, but the stick figure was inverted. In addition, participants were given the instructions from Experiment 5—no mention was made of force—and were told that the figure represented an inverted person. In all other respects, this experiment was identical to Experiment 4 (including feedback on force). Eight participants served as observers.

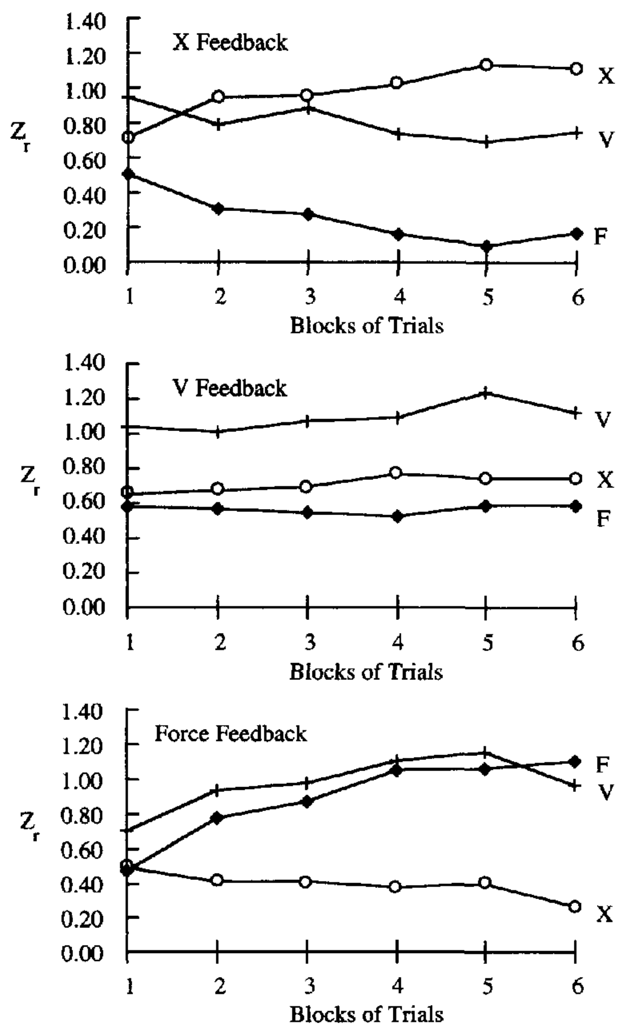

Figure 8. A plot of the three-way interaction of feedback type, predictor variable, and blocks of trials on the Z_rs for the zero-order correlations of judgment and predictor variables. The *X* and *V* feedback conditions were from Experiment 5, and the force-feedback condition was from Experiment 4.

Results and Discussion

The predictor graphs of individual participants (see Figure 9) were comparable to those presented for Experiment 4. They showed diversity in predictors among participants and systematic changes of predictor within participants. Thus, it appeared, at least qualitatively, that participants behaved similarly in the inverted version of the force perception task to the way they behaved in the upright version (Experiment 4). One also can ask whether the quality of the force judgments was the same in the two experiments. We compared the Z_rs for the correlations of judgment and force in the two experiments using a two-way ANOVA with experiments as a between-subjects factor and blocks as a within-subjects factor. The only significance was the expected main effect of blocks. This suggests that inversion does not appear to affect force judgments about stick figures in a stand-and-pull task.

Finally, a chi-square analysis examined the extent to which different predictors turned up significant in the inverted displays as opposed to upright ones (Experiment 4). There was an effect when all blocks of trials were included, $\chi^2(2, N = 100) = 7.03, p < .05$; 2% of the blocks had *X* as the single predictor, 40% of the blocks had *V* as the single predictor, and 58% had *V*-then-*X* (compared with 17%, 27%, and 56%, respectively, from the upright version), but the difference was attributable to the higher proportion of Block 1 *X*s in the upright condition. When Block 1 was ignored, the difference between upright and inverted was not significant. Again, there was no indication that the general patterns of results observed in Experiments 1–5 were unique to an upright human figure.

Experiment 7

The previous experiment suggests that the findings reported so far are about the perception of kinetics in general, not just the kinetics of human movement. If that is so, the simulation of an inanimate kinetic event would be expected to yield a similar set of results. This prediction was tested in Experiment 7. We asked participants to estimate the force applied to (or by) a simple inverted pendulum whose bob moved along the same trajectory as the center of mass in the previous experiments. We reasoned that if estimates derived

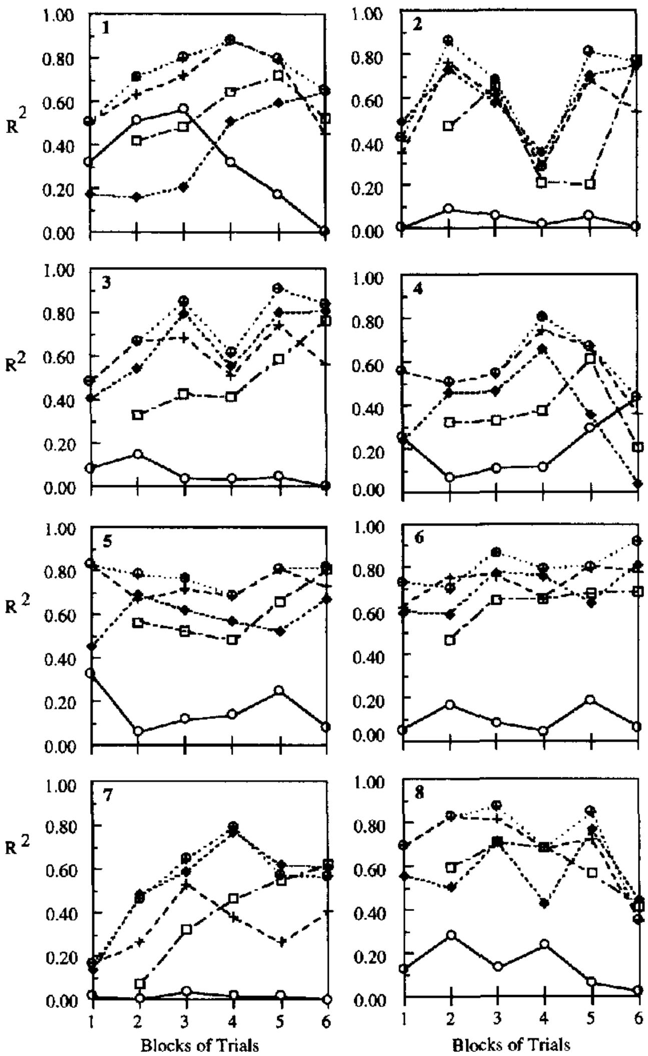

Figure 9. R^2s of the correlations of judgments with the various predictor variables in Experiment 6, in which judgments were given to an inverted stick-figure puller.

from the inverted pendulum yielded the same patterns of results as the human figures, it would provide further evidence of the generality of these effects.

Method

There were two conditions in the experiment; in one participants were given no feedback, and in the other force feedback was given. Twelve participants were paid for their participation. Four participants served in the no-feedback condition; 4 served in the feedback condition; and 4 served in both conditions, the no-feedback condition followed by the feedback condition. All were naive about the purpose of the experiment. They were asked to estimate the force exerted on an inverted pendulum. They did this by scaling a display against a standard inverted pendulum.

An IBM computer was used to generate the visual stimuli. The factorial combination of three levels each of torque, slack, and stiffness yielded 27 stimulus displays. The levels of torque were 2, 6, or 10 cm (· mg); the levels of slack were 5, 10, and 20 cm; and the stiffnesses were 5, 10, and 20 kN/m. The equation for the acceleration of the pendulum system (see Equation 2) was numerically iterated at intervals of 1 ms and the position of the bob read out every 20 ms (the refresh rate of the monitor). In addition to display parameters, the program computed the peak displacements, velocities, accelerations of the bob, and forces. The length of the pendulum plus bob on the screen was 8.4 cm; the cord was not represented.

Every trial consisted of two stimuli: a standard stimulus and a test stimulus. The standard stimulus, which was the same in every trial, showed a pendulum with a torque of 6, a stiffness of 10, and a slack of 5 and was assigned the arbitrary value of 10 force units. Participants were instructed to scale the force applied in the second stimulus with respect to the standard. Each stimulus was displayed for 5 s, which comprised 2–6 cycles depending on the combination of variables. Participants entered their estimates by keyboard. Four trials were given on each display in a completely randomized order in the no-feedback condition, and 5 trials were given in the feedback condition. Note that the kinematics of the displays were more like those used in Experiments 2 and 3 than those used in Experiments 4–6, in that slack was manipulated; that is, X and V were not artificially decorrelated (see Appendix B).

Results and Discussion

The correlations observed between judgments and the various predictors are presented for the no-feedback condition in Figure 10 and the feedback condition in Figure 11. Once again, we found the same family of effects observed earlier: Performance appeared to be better in the feedback conditions; judgments correlated more highly with lower order kinematic variables than with (a kinematic variable that specifies) force; individuals differed in the variables with which their judgments correlated most highly, and the variables with which judgments correlated most highly changed within participants. Additionally, the multiple regression analyses revealed that 3 of the participants in the feedback condition converged on the VX compound (Participants 1, 3, and 4 in Figure 11).

Although the inverted pendulum arguably yielded the same pattern of results that were observed with the stick figures, a comparison of Figure 11 with Figure 6 suggests that estimates on forces with the inverted pendulum were less reliable with respect to kinematics and less accurate with respect to force. To examine this difference, we combined the results of Experiments 2, 3, and 7. A three-way ANOVA (with stimulus type and feedback as between-subjects variables and blocks as a within-subjects variable) was performed on the Z_rs for the correlations of judgment and force. The results are presented in Figure 12. The judgments on the stick figures were better than those on the pendulum, $F(1, 29) = 6.63, p < .02$; judgments were better with feedback, $F(1, 29) = 18.77, p < .001$; and judgments improved over blocks, $F(3, 87) = 7.50, p < .0002$, although the significant interaction between blocks and feedback showed, not surprisingly, that improvement occurred only with feedback, $F(3, 87) = 4.62, p < .005$.

In short, there appeared to be differences in the extent to which participants could (learn to) estimate the kinetic properties of the two types of events. A stick figure was better than an inverted pendulum with comparable displacements, velocities, and accelerations. It was nevertheless the case that participants could learn to estimate the force in an admittedly unnatural display: an inverted pendulum that accelerated backward under its own power (in addition to gravity) and that was somehow jerked back to the vertical.

General Discussion

In seven experiments, participants estimated properties depicted in kinematic displays. They were asked to estimate the peak force exerted by (on) a real puller (Experiment 1), a stick-figure puller (Experiments 2–4), and an inverted pendulum (Experiment 7) and to estimate some unknown characteristic in Experiments 5 and 6, in which they were given feedback with respect to force, displacement, or velocity. The simulations depicted a locus (a pendulum bob

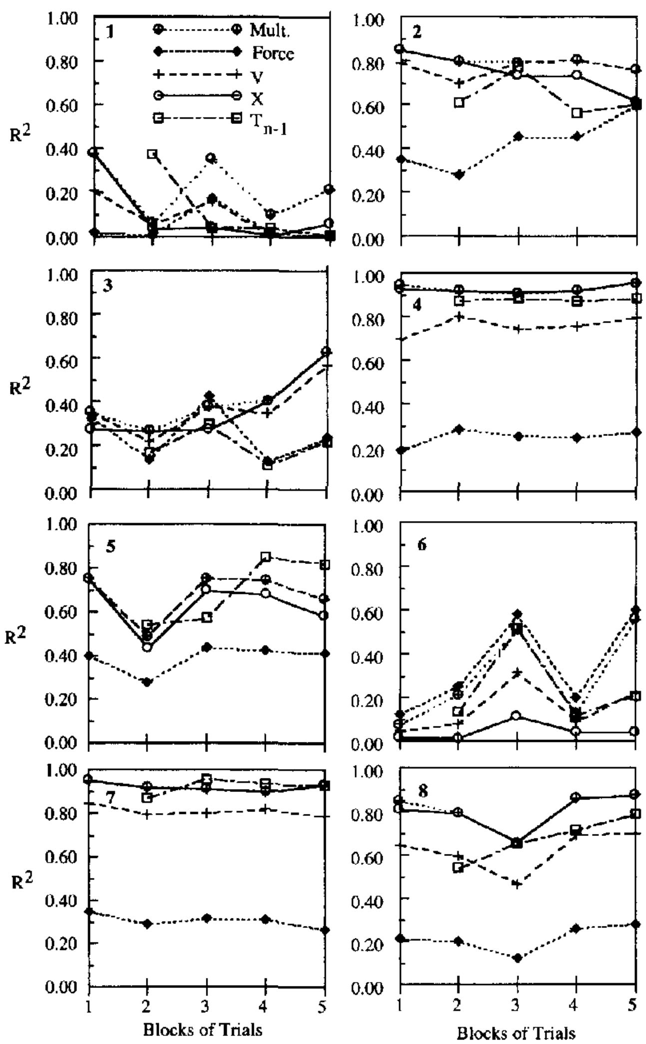

Figure 10. R^2s of the correlations of judgments of force applied to an inverted pendulum with the various predictor variables in Experiment 7 in the no-feedback condition. V = plus signs, X = open circles, T = trial, and n − 1 indicates the previous block of trials.

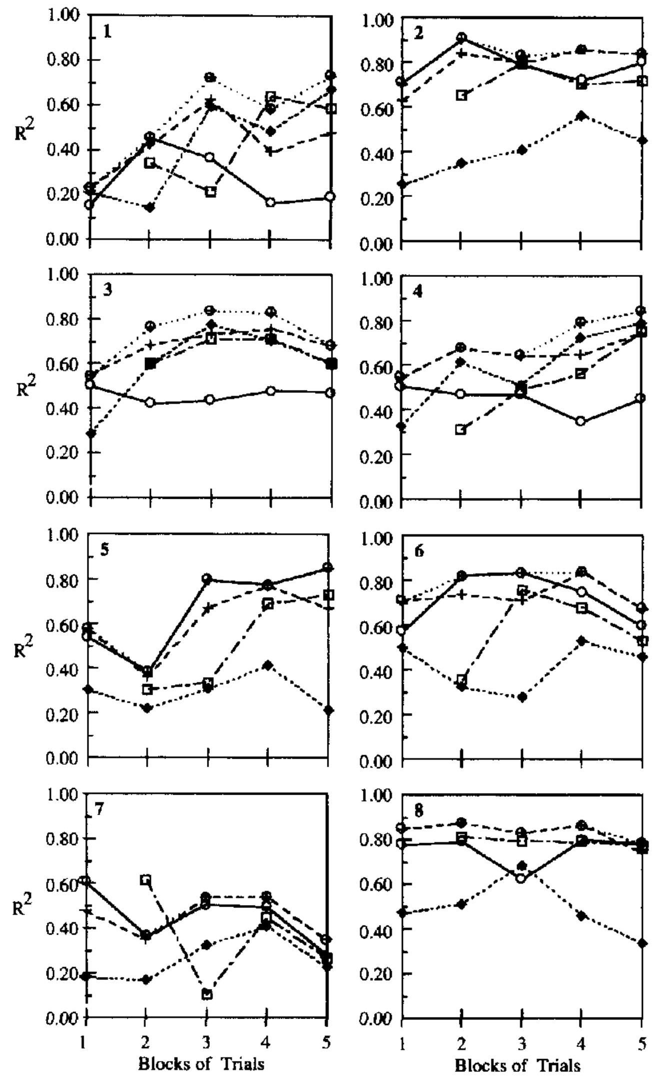

Figure 11. R^2s of the correlations of judgments of force applied to an inverted pendulum with the various predictor variables in Experiment 7 in the force-feedback condition.

or a center of mass location) that accelerated in a circular trajectory, both under the influence of a constant torque and an increasing torque caused by gravity. After traversing a particular horizontal distance (slack), the locus came under the influence of a spring that exerted a restoring force proportional to its stretch. The values of torque, slack, and stiffness were manipulated to yield arrays of 25 or 27 displays.

Overall, we conclude that participants did not show sensitivity to a kinematic variable specifying force. Two observations justify this conclusion: First, if participants had been sensitive to such a variable, correlations of judgment and force would have been at least as high as those for the judgment and individual kinematic variables. However, the estimations of force for all participants in all experiments, except for 1 block for 1 participant, had lower correlations with force itself than with kinematic variables (or com-

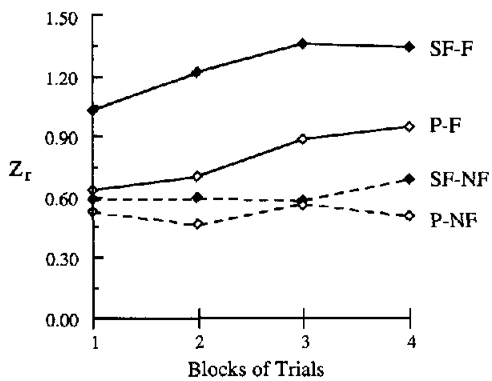

Figure 12. Average Z_rs for correlations of judgment and force with the inverted pendulum (P) and the stick figures (SF) either with feedback (F) or with no feedback (NF) from Experiments 7, 2, and 3, respectively.

pounds) that were not specific to force. With the exception of 3 participants in Experiment 2 (whose successive estimates on individual displays did not even correlate), we were able to track down kinematic sources that correlated more highly than force, even though in most of these experiments feedback on force was given. The second observation that denies usage of a kinematic variable specifying force was the individual differences among participants. Individuals' estimates appeared to be based on different variables, and changes over blocks of trials indicated that participants changed in the variables they exploited. The variables that participants exploited depended critically on feedback. This was evidenced first by the superiority of performance in those experiments in which feedback was given. Second, Experiment 5 (and its difference with Experiment 4) showed that the nature of the feedback determined, for most participants, which variable was exploited.[11]

Experiment 4 demonstrated that a variable that in and of itself was of no intrinsic use (i.e., had no zero-order correlation with force) could, as part of a compound with another variable, contribute to the accuracy of force estimates. We concluded in this instance that visual perception of pulling force evidenced the use of a compound (but still not force-specific) kinematic variable. Finally, Experiments 6 and 7 showed that the same pattern of results was observed when the stick-figure display was inverted and when a simple inverted pendulum was displayed. We interpreted this to mean that the observed phenomena reside in the general domain of the perception of kinetics per se and not only in the domain of the kinetics of biological motion.

This is a broad smorgasbord of results. The findings, together with the problem highlighted in the discussion of Experiment 4 (viz. the questionable value of the distinction between a kinematic variable that specified force and a kinematic variable that correlated .989 with force), set the stage for more nuance here than in the broad strokes of our introduction. It puts four items on the agenda: considerations of the (a) methodological implications and (b) possible limitations of our findings, (c) an elaboration of the concept of specificity, and (d) a view of perception and perceptual learning consonant with that elaboration.

Methodological Issues

Our results highlight a number of methodological issues for researchers who attempt to determine whether some variable provides the basis for perceptions of (or actions on) objects and events in the world. Many potential pitfalls have been discussed elsewhere. The discovery that manipulation of an informational variable has an effect on a dependent variable is of minimal interest; one needs to show that the quantitative change in the dependent variable is appropriate to the quantitative change in the informational variable (Michaels & Beek, 1995). Even when it is, the demonstration that the values of informational variables are appropriate to some perception or action does not guarantee that that variable was in fact used, as Tresilian (1993) emphasized with respect to judgments of time to contact and tau. Multiple regression analysis is no panacea for this problem; indeed, its indiscriminate use is virtually guaranteed to turn up spurious findings. Nevertheless, if one recognizes the dangers, especially when predictor variables are highly correlated, it does serve to narrow the field of probable variables.

As to avoiding the dangers, we have said little about the spadework done before regression analyses of judgments began: determining the relations among the kinematic variables and picking predictors. This includes ensuring that linear, rather than curvilinear or logarithmic, fits best capture the relations and eliminating (multi)collinear predictors. In eliminating (multi)collinear predictors from a regression analysis, however, one must not think that the problem of highly correlated kinematic variables is solved. The chosen predictor must stand in for its correlates. For example, in our experiments, acceleration was collinear with the compound of velocity and displacement; thus, a multiple correlation implicating both X and V would result if acceleration itself were the effective variable (see also Footnote 4). The cautious reader may therefore insert after each named variable or compound "and everything that is collinear with it." However, one should not exaggerate the danger; multiple regression analyses are less susceptible to this problem than ANOVAs. In general, one must be satisfied that regression analyses can serve only to eliminate particular variables rather than implicate them. The goal of this type of research is not to determine the identity or implementation of perceptual algorithms (e.g., the means by which V-then-X or acceleration is detected), but to determine what proximal patterns are exploited in a task. As such, the goal is to

[11] To discourage the possible conclusion that participants cannot judge force accurately without being trained to do so, we mention the results of another small experiment: Four participants (staff members in human movement science) were asked to estimate the percentage of possible pulling force of the 50 pulls while they were being taped for Experiment 1. Without feedback, individual participants achieved judgment–force correlations of $.85 < r < .95$.

determine what Marr (1981) termed the "computational problem" that appears to be solved in satisfying task demands. Determining how it is solved in terms of algorithms and how algorithms are implemented in tissue are tasks for network modelers and neuroscientists.

There also are a number of experimental design issues separating multiple regression and ANOVA approaches to investigating information-perception (or -action) dependencies. For the former, one must contrive display sets to have wide and well-populated ranges of predictor variables. Indeed, our own are sometimes on the meager side; it is recommended that one have at least 15 times as many observations as the number of predictor variables for each regression analysis (Cohen & Cohen, 1983); we had 50, 27, and 25 observations for our two-predictor regressions. That this holds for each multiple regression is especially burdensome if one is interested in tracking the use of predictors over the course of an experiment. It is equally important to have a broad and dense range of the response variable, which cannot be had with categorical judgments (e.g., which of the two balls is heavier or which of the two pulls is harder).

A final methodological note concerns the observation of differences between and within participants in the kinematic variables that best predicted their judgments. This finding emphasizes the value of analyzing raw data, data that have not been averaged over trials or participants. It is only with unaveraged data that the sorts of effects we reported here reveal themselves.

Limitations of Our Findings

In this section, we address the generalizability of the current findings. Is it realistic to expect that the trends and apparent principles revealed here will appear in other tasks? Three aspects of our task are of concern. The first is that we asked for numerical judgments. We tried to determine what observable properties of the optic array informed participants by asking them to say numbers. Admittedly, this is not in the spirit of the ecological ontology of perception and action. The choice was a matter of convenience. First, had we used an action as a measure of perception, we would have been confronted by an analog of the problem that we faced with perception, namely a host of observable action variables—a "muscular array"—that might be controlled by perceptual information. The problem of determining which of many possible, and perhaps highly intercorrelated, action variables is controlled mirrors the problem that we addressed, that of determining which of many possible perceptual variables is doing the controlling. The suggestion that participants might be asked to exert a bimanual pull in response to our displays is a possibility, but that strikes us as just another version of magnitude scaling that does not necessarily bring one closer to perception and action.

A second concern is that KSD experiments, including ours, put participants in the position of being passive recipients of information. Again, this is not in the spirit of ecological emphases on exploration and obtained information. At issue is whether the various findings are an artifact of requiring participants to make do with the information imposed on them. It may be that in other types of tasks in which participants are free to explore and manipulate, they might converge quickly and reliably on the same variable.

Even limiting the potential generality to the visual KSD experiments, a third concern is the complex of high intercorrelations of predictor variables and our arbitrary creation and relaxation of constraints (elaborated in the next section) to uncover what participants were doing. There is the possibility that we have unwittingly created the current array of phenomena: the use of lower order variables, individual differences, changing dependence on variables, and so on as mere learned strategies of how to respond.

On the one hand, one could argue that the situation we have created is so artificial that the results are generalizable only to other patently arbitrary KSD situations. On the other hand, the phenomena seem genuinely reliable; participants demonstrated, but not uniformly, an ability to adapt themselves flexibly and well to these task demands. That suggests to us that we may indeed have tapped a genuine form of perceptual learning—what Gibson (1966) called "the education of attention"—and in a way that lays it bare to careful scrutiny. Thus, that the task is arbitrary may be a virtue because it presents a paradigm for investigating the education of attention. In the next two sections, we take this assumption as our departure point and sketch out some implications for the ecological concept of information and for the debate among proponents of direct or directed perception and heuristics.

Specificity Versus Correlation

The specificity of information is an ecological, rather than logical or mathematical, concept. It is easy to lose sight of this in a cursory reading of the KSD principle, which emphasizes the natural law origins of kinematics and underplays other constraints. Runeson (1988) borrowed Barwise and Perry's (1983) term *nomic constraints* to capture the fuller picture: "Nomic constraints include not only universal laws of nature but also natural regularities that are conditional in the sense that they apply locally or when certain conditions prevail" (Runeson, 1988, p. 300). Natural law and constraints are both, in Runeson's terms, *grantors of information.* Runeson (1989; Runeson & Vedeler, 1993) used the term *incomplete invariants* to denote invariants based, in part, on local constraints, although we wonder whether any qualifier is needed, in that "complete invariants" rely on "general characteristics of terrestrial environments" (Runeson, 1989, p. 7). A few examples may clarify how constraints grant information. That terrestrial gravity is 9.8 m/s grants acceleration, ceteris paribus, potential information about size and distance. That size is an enduring characteristic for some objects grants tau, ceteris paribus, potential information about time to contact. That eye height is an enduring characteristic of animals, that gravity prevails, and that the horizon is visible (or specified) grants texture gradients, ceteris paribus, information about sizes and distances of objects.

The relevance of constraints to the present task is obvious in our explicit attempts to decorrelate variables. In response to excellent force estimation and highly intercorrelated variables in both Experiments 1 and 3, we altered constraints to lower the correlations among variables. At the end of our discussion of Experiment 1, we noted that the task demand on a puller to generate accurate force may constrain how many variables are controlled in the production of a pull and that that cramped the space of variables, permitting participants to "get away" with using only velocity. However, that logic implicitly dismissed the possibility that constraints on pull production are grantors of information and the positive observation that participants exploited that constraint in their judgment. In the ecology of real pulling, the observed constraint of constant stiffness (Michaels & Lee, 1996) grants *V* the status of information about force.

In short, in relaxing constraints on a real puller (Experiment 1) to create the simulations of Experiment 2, we reduced the information available. In adding a new constraint (constant slack) for the displays in Experiment 4, we created the informative compound of *V*-then-*X*, and 5 of the 8 participants learned to exploit it. These three experiments thereby differed in the potential information that they offered. Therefore, it is not surprising that we found different levels of performance, as shown in Figure 13.

These considerations do not adjudicate the problem of whether specification or correlation provides the better description of the relation between proximal patterns and distal properties. However, the concept of information entails not only that relation, but also a perceiver who might pick it up, and a task to be accomplished. Within task ecology, one might reserve the term *specificity* to refer to whether the available information is such that task demands can be satisfied, presumably to be determined a posteriori. Correlations, then, become measures that are meaningful only within a task, where they permit comparison of variables and prediction of limitations on performance.

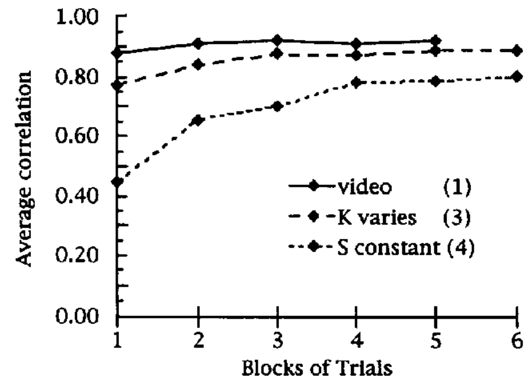

Figure 13. Average correlations of judgment and force over blocks of trials for Experiments 1, 3, and 4. One constraint on real pulling, constant stiffness, was relaxed in Experiment 3. A different (and unnatural) constraint, constant slack, was added in Experiment 4. Performance therefore appeared to be related to how closely the display constraints matched the constraints of real pulling.

Perception and the Education of Attention

We began our experiments with the hope of adding to the understanding of the perception of kinetics and the type of theory that accounts for that perception. We began with three contemporary candidates: direct perception, directed perception, and heuristics.[12] The direct perception approach argues that perceivers should show sensitivity to a kinematic variable that specified force. We did not find that although one could argue that our participants, if they had been given more practice and feedback, might have been able to discover or direct their attention to a kinematic variable specifying force. However, it is clear that over the range of trials that we ran, up to 250, such sensitivity was not evident. The notion that pulling force was directly perceived via kinematics that uniquely specify force was thereby rejected.

On the other hand, we found that judgments were tightly bound to observable quantities in the visual array. It did not seem that proximal stimulus variables disappeared into the person, mixed with a muddied naive physics, were weighted and transformed, to emerge as an unrecognizable ingredient in a perceptual judgment. The behavior of individuals was different but nonetheless lawful; the systematic variance in perception was attributable to variation in proximal patterns. Therefore, we emphasize that participants' reliance on lower order variables does not necessarily imply an inferential process. One can still hold an uncompromising relationship between perception (or action) and the sensory variables that are detected, their specification of physical properties of the environment aside. People detect what they detect; it is the scientist's intuitions about people's goals that turns that

[12] One theoretical position that we have not aired here is Brunswik's (1956) probabilistic functionalism. Many of Brunswik's concerns were the same as our own. He sought to determine the "ecological validity" of a proximal stimulus, which he measured as the correlation between a proximal pattern and a distal property, as in that between kinematic patterns and kinetics. He tried to determine the "functional validity" of proximal patterns, whether participants exploited them in accomplishing a task, obviously what we have done in this research. One might even go as far as to suggest that the use of a compound variable is what Brunswik foresaw in his "lens model." We think, however, that the parallels stop there. Brunswik's (1956) perceptual theory had perceivers picking and choosing from among proximal variables, assigning them different weights by virtue of relative frequencies of association with the distal property. Instead, the position we advocate is that perceivers reliably attend to and detect certain variables to constrain their judgments and actions without making further decisions, assigning weights, and so on. The "choice" is in attention to a variable; thereafter perception is specific to that variable. On some other occasion, a perceiver may attend to some other variable, but it, too, will directly inform perception and action.

detection into inferences or, as Gibson (1966) noted with respect to illusions, into perceptual errors.[13]

Given the construal of information as granted both by natural law and by constraints (be they lawful or arbitrary), every task has an "ecology." If the goal of perceptual learning is the discovery of a perceptual variable that is sufficient to satisfy the task demands on judgments or actions in that ecology, our results may provide some insight into the process by which access is gained to such variables. It does not appear to be the case that a person stumbles onto the proper variable and thereafter "directly perceives." Instead, merely correlated variables appear to guide the search for and come to be selected as integral parts of an informational complex. Our results highlight the need for a careful elaboration of the Gibsonian concepts of "the education of attention" and "perceptual differentiation" (Gibson, 1966) and implicate the use of lower order variables in that process. Although it is beyond the scope of this article to consider how education of attention to a compound variable might be learned (or evolved), our results yield the following speculations.

The role for the perceiver in the task is to become an expert, insofar as motivation and causal support for expert performance permits. As causal support, we include information available for detection and smart perceptual devices (Runeson, 1977) suitable for the detection of that information. When a smart perceptual device exists (evolved or learned) and the appropriate information is available and the perceiver intends to perform, he or she will behave like an expert.

The task ecology changes with changes in available information. The perceiver will be inclined to explore the information space until the task demands are met. Educating attention also can involve the development of a smart perceptual device. One can imagine, on first pass, a process analogous to Bernstein's (1967) beginner's solution to the degrees of freedom problem in coordinated action. Confronted with a large number of motor elements to control, the beginner freezes many and manipulates as few as possible, yielding a stiff performance. When that simple version of the action is mastered, the beginner successively relaxes constraints and incorporates additional degrees of freedom. A "coordinative structure" (Turvey, 1977) is developed in which many degrees of freedom come to be controlled as a single unit. Similarly, the novice perceiver is confronted by a plethora of possible perceptual variables to guide judgment (or action); one is chosen (the others frozen out) and a serviceable performance emerges. In time, additional variables may be successively introduced and a smart device develops, a perceptual analog to a coordinative structure that collects entities together so that they function as a single unit: information. At various points in perceptual learning and under various circumstances, individuals would behave as if their perception were direct, directed, or based on heuristics. However, the undercurrent is the same: Individuals educate their attention to useful information that permits them to satisfy task demands given the ecology of the situation.

[13] The Gibsonian (Gibson, 1966) sword that undercuts the argument from illusion also can be turned on the perception of kinetics. If we think it is an act of hubris to declare that people are in error when they report that the length of a line is different from what a ruler measures, it also is an act of hubris to expect that perceptual systems register kinetic properties, say, as measured by force transducers. The alternative is to adopt a more humble stance with respect to what perceivers are doing, behaving pragmatically in a task setting, and let the chips fall where they may (cf. Shaw, Turvey, & Mace, 1982; Warren, Kim, & Husney, 1987).

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(Appendixes follow)

Appendix A

The Inverted Pendulum Model

Here we summarize the derivation of Equations 1 and 2, which describe the center of mass motions in the stand-and-pull task and their modeling as an inverted pendulum (from Michaels, Lee, & Pai, 1993, Appendix B; their Appendix A, not summarized here, captures the biomechanics of pulling in a four-segment model). Equation A1 relates the net torque, T_N, about the axis of rotation to the torques associated with muscular forces about the ankle (T_A, assumed to be constant), gravity (T_G), and the force of the pull created in the model by an elastic cord (T_E):

$$T_N = T_A + T_G - T_E, \tag{A1}$$

where

$$T_G = mg \cdot X \tag{A2}$$

$$T_E = K(X - S) \cdot r \cos \Theta. \tag{A3}$$

The equation for T_G shows that the anterior–posterior distance (X) from the ankle to the center of mass is the moment arm of a torque caused by the gravitational force. For T_E, the cord is assumed to exert a force linearly proportional to its stretch (X less the slack, S, in the cord) and to its stiffness, K. The pulling force is only in the horizontal direction, so its torque is a cosine function of the angle of the pendulum, Θ. T_E is zero when $X \leq S$.

T_N gives rise to an angular acceleration, which is computed by dividing the torque by the moment of inertia of the pendulum (mr^2, where m and r are the pendulum mass and length, respectively) as shown in Equation A4. The horizontal component ($\ddot{X}$) of that angular acceleration is given in Equation A5:

$$T_N = \ddot{\Theta} mr^2 \tag{A4}$$

$$\ddot{X} = \ddot{\Theta} \cdot r \cos \Theta - r \cdot \dot{\Theta}^2 \cdot \sin \Theta. \tag{A5}$$

Given the values of Θ (<15°) and the small angular velocities that develop, the velocity term in Equation A5, $r \cdot \dot{\Theta}^2 \cdot \sin(\Theta)$, can be omitted. Making the resulting substitutions in Equation A1, we have the following:

$$\frac{\ddot{X}}{r \cos \Theta} \cdot mr^2 = T_A + mg \cdot X - K \cdot (X - S) \cdot r \cos \Theta. \tag{A6}$$

Treating ankle torque as a force (mg) acting through a moment arm, CP (ankle to center of pressure), and simplifying, we end up with the following:

$$\ddot{X} = \left[\frac{(X + CP) \cdot g}{r} - \frac{K \cdot (X - S)}{m} \cdot \cos \Theta\right] \cdot \cos \Theta, \tag{A7}$$

where

$$\cos \Theta = \frac{\sqrt{r^2 - X^2}}{r}, \tag{A8}$$

which is given in Equation 2 as W.

Appendix B

Correlations Among Variables for All Stimulus Sets

Variable	X	V	A
	Experiment 1		
V	.970	—	—
A	−.953	−.979	—
Force	.952	.975	−.987
	Experiments 2 and 3		
V	.954	—	—
A	−.808	−.910	—
Force	.854	.953	−.991
	Experiments 4–6		
V	.618	—	—
A	.321	−.535	—
Force	−.055	.743	−.963
	Experiment 7		
V	.918	—	—
A	−.210	−.548	—
Force	.556	.823	−.924

Received March 14, 1994
Revision received December 12, 1996
Accepted January 22, 1997 ■